Gluon EMC effect and fractional energy loss in Υ production in dAu collisions at RHIC

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Abstract

We argue that the Υ nuclear modification factor, $R^{\Upsilon}_{d\mathrm{Au}}$, measured at RHIC can only be reproduced once gluon EMC effect and fractional energy loss are taken into account. At backward rapidities, the visible suppression of $R^{\Upsilon}_{d\mathrm{Au}}$ hints at the presence of a gluon EMC effect, analogous to the quark EMC effect – but likely stronger. At forward and mid rapidities, the data can only be accounted for by a *fractional* energy loss, recently revived in the literature. Our conclusions do not depend on the detail of the nuclear parton distributions. Such a fractional energy loss also provides an alternative explanation to gluon saturation for the strong forward J/ψ suppression in dAu collisions observed by PHENIX.

1 Introduction

Conventional nuclear modifications of gluon distribution in heavy ions – known as shadowing and anti-shadowing – as well as the possible break up of the $b\bar{b}$ pair along its way off the nucleus are shown to have a limited impact on the Υ production in dAu collisions at RHIC at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$. Without additional effects, one fails to reproduce the nuclear modification of the yield measured by the STAR and PHENIX experiments [1, 2].

This discrepancy motivated us to study the impact of two additional nuclear effects. The first is a suppression of gluon distribution in nuclei for intermediate Bjorken-x, $0.35 \leq x_B \leq 0.7$, analogous to the quark EMC effect [3], unobserved until now. The second is a *fractional* energy loss [4] proportional to the projectile parton energy and caused by medium-induced radiations associated to the quarkonium hadroproduction. This radiative energy loss arises when radiation off the incoming parton and outgoing coloured object is nearly coherent, which happens when the flow of color charge undergoes a small angle scattering in the nucleus rest frame. Such *fractional* energy loss is thus still relevant at RHIC energies, contrary to the usual radiative

energy loss [5] where a hard parton is suddenly produced (or undergoes large angle scattering) in a static medium.

We have compared our results –from our Monte-Carlo framework JIN [6]– to dAu Υ data from RHIC experiments [1, 2] and found a good agreement *only* when including both additional effects. We also found a good agreement with dAu J/ψ data when the effect of energy loss is combined with mild gluon shadowing and a small value for the effective absorption cross section. In particular, the energy loss provides an alternative explanation to gluon saturation –or strong shadowing– for the strong forward J/ψ suppression in dAu collisions observed by PHENIX. Whereas, in the Υ case, energy loss seems to be required since no other effect can explain the forward data, energy loss is only one of the possible effects responsible for forward J/ψ suppression. The situation is indeed less clear for J/ψ since shadowing and/or saturation as well as the break-up probability can also have a significant impact [6].

2 Propagation in cold nuclear matter: Υ vs J/ψ

The first effect to be discussed is the probability for the heavy-quark pair to survive the propagation through the nuclear medium, usually parametrised by an effective cross section $\sigma_{\rm eff}$. It is sometimes referred to as the nuclear absorption or break-up probability.

A priori, the smaller size of the $b\bar{b}$ pair when compared to $c\bar{c}$ pair implies that $b\bar{b}$ states should suffer less break-up than $c\bar{c}$. Yet, the ratio of their size depends on the evolution stage of the heavy-quark pair. At the production time, this ratio is expected to be m_b/m_c, hence a size 3 times smaller for $b\bar{b}$ than for $c\bar{c}$. When they are fully formed, it is rather $\frac{\alpha_s(2m_b)}{\alpha_s(2m_c)} \times \frac{m_b}{m_c}$ as expected from their Bohr radii, hence a size 2 times smaller. The relevant timescale for the pair evolution is the formation time. According to the uncertainty principle, it is related to the time needed – in their rest frame – to distinguish the energy levels of the $1S$ and $2S$ states [7]: $t_f = \frac{2M_{b\bar{b}}}{(M_{2S}^2 - M_{1S}^2)} = 2 \times 10$ GeV / 10.5 GeV^2 = 0.4 fm for the Υ.

For our purpose, t_f has to be considered in the rest frame of the target nucleus, *i.e.* the Au beam at RHIC. The relevant γ factor is then obtained from the rapidity of the pair corrected by the Au beam rapidity $\gamma = \cosh(y - y^{\rm Au}_{beam})$ where $y^{\rm Au}_{beam} = -5.36$ for RHIC. The formation time for the different rapidities reached by RHIC experiments are given in Table. 1. t_f is significantly larger than the Au radius – except in the most backward region. This implies that the $b\bar{b}$ is nearly always still in a pre-resonant state when traversing the nuclear matter.

Table 1: Υ boost and formation time in the gold rest frame as a function of its rapidity at $\sqrt{s_{NN}} = 200$ GeV.

y	γ	t_f	y	γ	t_f
-2.0	14.4	5.8 fm	0.0	106	42 fm
-1.5	23.7	9.5 fm	+1.5	476	190 fm
-1.0	39	16 fm	+2.0	786	310 fm

For the forward and mid rapidity regions, this has two consequences : first, the break-up probability is expected to be small, of the order of a tenth of that of J/ψ ($(m_c/m_b)^2 \sim 0.1$),

following the early-time scaling m_b/m_c; and second, it ought to be the same for the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ states, since these states cannot be distinguished at the time they traverse the nucleus. At the LHC, t_f's are even larger; excited Υ state suppression in PbPb collisions seen by CMS [8] can thus only be explained by hot nuclear effects.

The backward region at RHIC requires a closer look. Indeed, for the same t_f, of the order of 15 fm, the E866 experiment at Fermilab [9] observed a different suppression of J/ψ and $\psi(2S)$ produced with Feynman x_F up to 0.2 at $\sqrt{s_{NN}} = 38.8\,\text{GeV}$. We might thus expect different absorption cross-section for the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ states for $y < -1$. However, the E772 experiment at Fermilab [10] has measured the $\Upsilon(1S)$ and $\Upsilon(2S + 3S)$ separately at $\sqrt{s} = 38.8$ GeV down to negative x_F – with even smaller t_f – and it observed a similar suppression for the $1S$ and the $(2S + 3S)$ states The only explanation for such a result is that the absorption of the bottomonium is actually very small, preventing us to see any difference of absorption between the 3 states. In the following, we will consider a range of σ_{eff} from 0 to 1 mb even though 1 mb has to be seen as a conservative upper bound.

3 Gluon momentum distribution in nucleus

At high energy (small x_B), the nuclear Parton Distribution Functions (nPDF) differ from those of free nucleons due to non-linear QCD effects. Nucleons *shadow* [11, 12] each other and the nPDFs are expected to be lower than for free nucleons. At $0.01 \leq x_B \leq 0.3$, some experimental data hint [13] at an excess of partons with regards to unbound nucleons, referred to as anti-shadowing. For $0.35 \leq x_B \leq 0.7$, the distribution is depleted again. This suppression is known as the EMC effect.

These nuclear modifications are usually expressed in terms of the ratios R_i^A of the nPDF of a nucleon bound in a nucleus A to the free nucleon PDF. The numerical parametrisation of $R_i^A(x_B, Q^2)$ is usually given for all parton flavours. Here, we limit our study to gluons since, at RHIC, Υ is essentially produced through gluon fusion [14, 15]. To best explore the possible impact of R_i^A, we have considered 3 sets: EKS98 [16], EPS08 [17] and nDSg [18] at LO. Recently, a new set with fit uncertainties, EPS09 [19], has been made available. Yet, in the case of gluons, nDS and EPS08 match –except for $x_B \geq 0.3$– the extreme values of EPS09. Besides EKS98 is very close to EPS09 central values. We thus consider more illustrative to use EKS98, EPS08 and nDSg. The spatial dependence of PDF nuclear modification has been included with a modification proportional to the local density [20]. Following the common practice, we label x_1 (x_2) the gluon momentum fraction in the proton/deuteron (nucleus).

Thirty years ago, the European Muon Collaboration (EMC) [3] observed a depletion of the quark densities in nucleons bound in nuclei, when compared to the ones of free nucleons, in the range of $0.35 < x_B < 0.7$. To date, there is no consensus [21] about the origin of this suppression, referred to as the EMC effect. It is still the subject of vivid activities. It has been attributed to local nuclear density effects, to properties of the bulk nuclear system, and recently [22] to Short Range Correlations (SRC) in the nucleus. Up to now, this effect has not been confirmed for gluons, even if it is allowed in some of the shadowing fits.

While gluon shadowing in the existing nPDF constrained fits, especially in EPS 08 & 09,

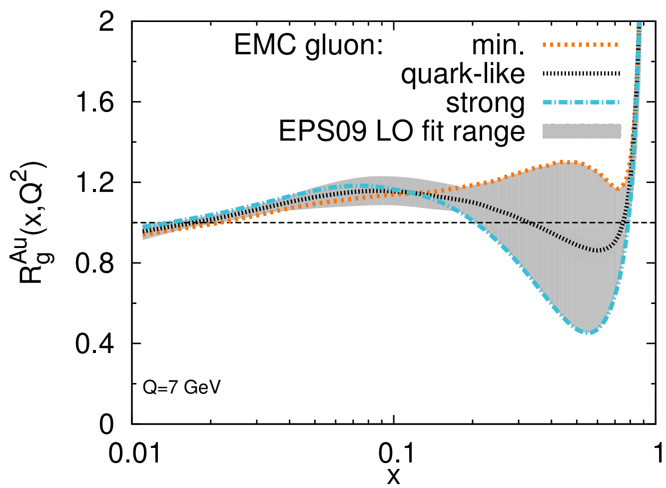

Figure 1: The 3 gluon nPDF sets we have used to single out the EMC effect and the corresponding EPS09 uncertainty for Au.

is the subject of intense on-going debates, the gluon EMC suppression is usually overlooked. Indeed, very little is known about gluons in this region and few data constrain their distribution at x_B larger than 0.3. The amount of the EMC suppression is actually pretty much unknown [19], except for a loose constrain set by momentum conservation. We also note that another effect [23] arising from momentum conservation within the nucleons could be at play at larger x_B, $x_B \geq 0.7$, *i.e.* at larger y or smaller $\sqrt{s_{NN}}$, and hence it is not applicable here.

To single out a possible impact of the EMC gluon suppression on Υ, we have used three of the EPS09 LO sets: one with a quark-like EMC gluon suppression, and the two limiting curves in the region $0.35 < x_B < 0.7$ (Fig. 1). As the data-theory comparison will show, its magnitude indeed seems stronger than what has been previously supposed in the existing nPDF sets (which assumed a quark-like EMC gluon suppression) and disagrees with a Fermi-motion enhancement down to $x_B \simeq 0.5$ as expected in [24].

In practice, to account for the nuclear effects on Υ production in nucleus collisions, we use our Monte-Carlo framework JIN [6], based on the probabilistic Glauber model, used to describe J/ψ production at RHIC [25, 26]. It allows to consider improved kinematics corresponding to a $2 \rightarrow 2$ ($g + g \rightarrow b\bar{b} + g$) partonic process for the Υ production (as in the Colour-Singlet Model (CSM) at LO [27]). In earlier studies of nuclear matter effects on Υ production [28], the $b\bar{b}$ pair was assumed to be produced by a $2 \rightarrow 1$ partonic process ($g + g \rightarrow b\bar{b}$).

4 Energy loss

An energetic parton travelling in a large nuclear medium undergoes multiple elastic scatterings, which induce gluon radiation, hence a radiative energy loss. Effectively, since the parton loses energy, the quarkonium hadroproduction process probes the incoming proton PDF at a higher

$x_1' = x_1 + \Delta x_1$, leading to nuclear suppression since the gluon PDF $g(x)$ at $x = x_1'$ is smaller than the one at $x = x_1$, $g(x_1') < g(x_1)$.

Twenty years ago, parton energy loss in nuclear matter was suggested to be the dominant effect responsible for both Drell-Yan and J/ψ suppression [29] at forward x_F. It was assumed to scale with the incoming parton energy, $\Delta E \propto E$, while being a medium-induced energy loss of an independent colour charge taking place in the medium and not in the vacuum. However, general quantum mechanical arguments based on the uncertainty principle seem to lead to the bound $\Delta E \leq L\langle k_T^2\rangle$ [30], where L is the size of the medium and $\langle k_T^2\rangle$ is the average transverse momentum squared of the radiated gluon. Such medium-induced energy loss therefore cannot scale with the parton energy E when $E \to \infty$.

Recently [4], it has nevertheless been pointed out that, in the case of small angle quarkonium production, the medium-induced spectrum *also* arises from large formation times $t_f \gg L$. The uncertainty principle does not constrain anymore the radiation and the medium-induced "energy loss" scales as the energy E in apparent contradiction with [30]. The contradiction is solved by noting that the "loss" derived in [4] is not the loss of an independent parton suddenly produced, but the amount of gluon radiation associated to the quarkonium production process. This applies for octet-like mechanisms where the heavy-quark pair is produced at short distances in a colour-octet state – the latter can thus radiate. This is so in the Colour-Evaporation Model (CEM) and the Color-Octet Mechanism (COM) (see [14, 15]). For singlet-like mechanisms – such as the CSM – the energy loss will occur only when the heavy-quark pair is produced at short distances (in a colour-singlet state) in conjunction with at least one hard gluon (or quark). This is the case in our CSM LO $2 \to 2$ ($g + g \to \Upsilon + g$) process valid at low p_T [27], but also at higher-orders in α_S with 2 or 3 coloured partons in the final state [31, 32].

One then finds [4] that for forward angle Υ production in pA collisions, the fraction of medium-induced radiated energy is given by $\Delta E/E = \Delta x_1/x_1 \simeq N_c\alpha_s\sqrt{\Delta\langle p_T^2\rangle}/M_T$, where $\Delta\langle p_T^2\rangle$ is the broadening of the radiated gluon from the proton and M_T is the transverse mass of the final-state coloured object. We assume the gluon broadening to be equal to the Υ broadening, $\Delta\langle p_T^2\rangle \equiv \langle p_T^2\rangle(A) - \langle p_T^2\rangle(^2\mathrm{H})$, proportional to the length of nuclear matter seen by the incoming parton. This broadening in p_T^2 is consistent with a dependence on $A^{1/3}$, as expected in multiple scattering models. Taking the E772 value measured with W target [33, 10], $\Delta\langle p_T^2\rangle = 0.410$ GeV^2, one can thus write $\Delta\langle p_T^2\rangle = 0.072$ GeV^2 $A^{1/3}$.

In octet-like mechanisms, M_T is the mass of the quarkonium bound state, here $M_T \sim 10$ GeV. For singlet-like production, M_T is rather the mean p_T of the final-state gluon. We have taken $M_T = 3.0$ GeV here. For $N_c = 3$ and $\alpha_s = 0.2$, we have $\Delta x_1^{singlet}/x_1 \sim 13\%$ in the singlet case, and about three times lower, $\Delta x_1^{octet}/x_1 \sim 4\%$, in the octet case. As we shall see, this makes a visible difference in the yield suppression. At $\sqrt{s_{NN}} = 200\,$GeV, the average x_1 of the projectile gluon in the forward rapidity region, $1.2 \leq y \leq 2.2$, is $\langle x_1^{fwd,\Upsilon}\rangle = 0.28$. In the mid rapidity region, $\langle x_1^{mid,\Upsilon}\rangle = 0.05$. The corresponding suppression is just the ratio between the PDF of the gluon evaluated at its original x_1', $x_1' = x_1 + \Delta x_1$ before the loss and the PDF at the resulting x_1: $R_{loss}(x_1, Q^2) = g(x_1', Q^2)/g(x_1, Q^2)$.

Before evaluating the corresponding yield suppression, it is important to note that, in the CSM, χ_{b2} production at LO does not produce a recoiling gluon and is not affected by such an

effect. We evaluate it to be 10 % of the Υ yield. In the other cases, the feed downs are expected to be suppressed as much as the direct yield in the corresponding model. Taking modern global-fit gluon PDFs, one finds that this *fractional energy loss* gives $R_{loss}^{singlet} = 65\% \div 70\%$ and $R_{loss}^{octet} = 85\% \div 90\%$ at forward rapidity. At mid rapidity, there is still a suppression due to this energy loss effect, which induces $R_{loss}^{singlet} \sim 80\%$ and $R_{loss}^{octet} \sim 90\%$. We have recomputed these numbers using different modern LO PDF sets and have found that our result lies well in this range. We consider the overall uncertainty on $1 - R_{loss}$ to be of the order 10-20 %, *i.e.* clearly smaller than that of the data.

We have also studied the impact of the energy loss effect on J/ψ production. Due to the smallness of M_T compared to the Υ case, we have $\Delta x_1^{singlet}/x_1 \sim 20\%$ and $\Delta x_1^{octet}/x_1 \sim 10\%$. Both losses are stronger than for the Υ. Yet, at $\sqrt{s_{NN}} = 200\,\text{GeV}$, $\langle x_1^{fwd,J/\psi}\rangle \sim 0.1$ and $\langle x_1^{mid,J/\psi}\rangle \sim 0.02$, *i.e.* smaller than for Υ. Hence, one has $R_{loss}^{singlet} \sim 70\%$ and $R_{loss}^{octet} \sim 80\%$ for forward J/ψ. At mid rapidity, the induced suppression is $R_{loss}^{singlet} \sim 80\%$ and $R_{loss}^{octet} \sim 90\%$, similarly to the Υ case. These should however be combined with the suppression from the shadowing and nuclear breakup which –contrary to the Υ case– are not negligible.

At backward rapidities, the typical formation times are of the order of the nucleus size and the conditions of the applicability of the derivation of ΔE in [4] are not satisfied. In addition, due to the behaviour of the gluon PDFs at small x_B, one would find a smaller effect than at $y \geq 0$, if one were tempted to apply the same formula without much concern.

5 Results for dAu collisions

Experimentally, Υ and J/ψ suppressions are studied by measuring a *nuclear modification factor* $R_{d\text{Au}}$, the ratio of the yield in dAu collisions to the yield in pp collisions at the same energy times the average number of binary inelastic nucleon-nucleon collisions N_{coll} in a dAu collision: $R_{d\text{Au}} = (dN_{d\text{Au}})/(\langle N_{\text{coll}}\rangle dN_{pp})$. Any nuclear effect affecting Υ and J/ψ production leads to $R_{d\text{Au}} \neq 1$.

From STAR and PHENIX [1, 2] only the rapidity dependence is known. For now, the 3 Υ resonances are not resolved but are measured together. Since the nuclear absorption has to be small and since the nPDF effects are very likely similar for these 3 states, we can safely consider them on the same footage. However, it is worth noting that a future measurement of $R_{d\text{Au}}$ focusing only on $\Upsilon(1S)$ would be very precious to confirm this assumption.

Fig. 2 (a) shows the uncertainties on R_{dAu} vs y due to the lack of knowledge on gluon nPDF and due to a variation of σ_{eff} between 0 and 1 mb. Gluon shadowing (at forward y) and anti-shadowing (at mid y) are not strong enough to match the RHIC data. The nuclear absorption also shows a very mild effect, which is insufficient to reproduce the data, especially since 1 mb is likely exaggerated. At backward y, a gluon EMC effect stronger than that of quarks, such as the one provided by the EPS09 lower bound, gives a very convincing account of the backward data (see Fig. 2 (b)). This modification does not alter the results at mid and forward rapidities and is perfectly legitimate given the current knowledge of the gluon nPDF in this region. It is nevertheless clear that experimental uncertainties are large and the observation of such a strong EMC gluonic effect would only be confirmed once we have data with reduced errors. The data

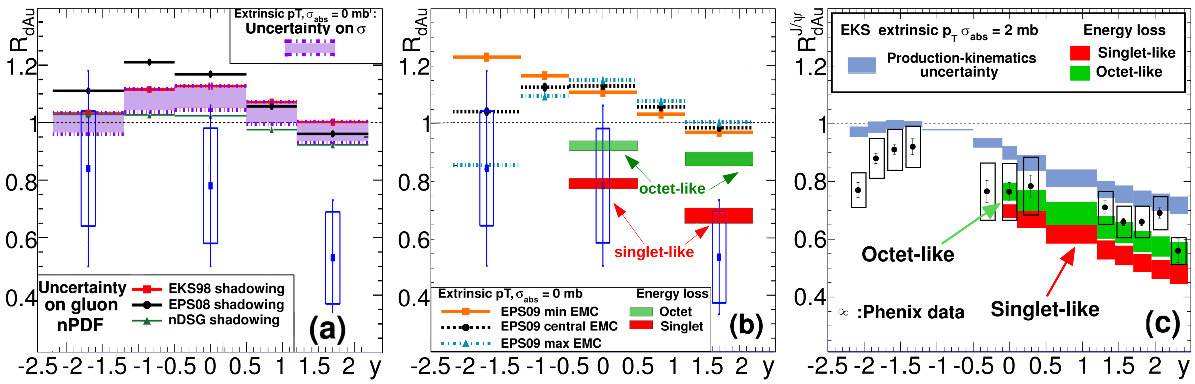

Figure 2: (b) Theoretical uncertainties on $R^{\Upsilon}_{d\mathrm{Au}}$ due to the nPDF (coloured lines) and σ_{eff} (purple band).; (c) Effect of an increase of the gluon EMC effect and of the fractional energy loss for singlet-like (red band) and octet-like (green band) production at small angles ($y > 0$) on $R^{\Upsilon}_{d\mathrm{Au}}$. (d) $R^{J/\psi}_{d\mathrm{Au}}$ from [26, 34] (top blue band) for $\sigma_{\mathrm{abs}} = 2$ mb with the fractional energy loss for singlet-like (red band) and octet-like (green band) production at small angles. Data for Υ are from [1, 2] and for J/ψ from [36].

however already visibly disfavour the case with no gluon EMC effect (orange solid bars).

We now discuss the effect of the fractional energy loss. Fig. 2 (b) clearly shows its impact in the mid and forward regions. The green bands indicate the suppression expected for octet-like productions, and the red bands for a singlet-like production. The second case – with a stronger suppression – better matches the data which cannot otherwise be accounted for. Going further in the interpretation, we could say that the significant suppression of Υ in the forward region favours a production mechanism where the heavy-quark pair is produced at short distances in a colour-singlet state in association with one or more gluons.

Such energy loss also impacts J/ψ production, as shown Fig. 2 (c), where our previous results with EKS98 [26, 34], for an ad hoc $\sigma_{\mathrm{abs}} = 2$ mb, are combined with the additional suppression induced by the energy loss. Our results are qualitatively confirmed by a recent analysis [35] where energy loss is also shown to reproduce the most forward fixed target data at lower energies. Agreement with PHENIX data [36] is obtained especially if one assumes σ_{abs} to be negligible as done in [35]. In particular, the suppression due to the energy loss has a steeper y dependence than that of shadowing.

6 Conclusion

We have investigated Υ suppression in dAu collisions at $\sqrt{s_{NN}} = 200$ GeV. The rapidities covered by RHIC experiments allow for a unique study of cold nuclear matter effects and revealed unexpected features presented here. Backward rapidities correspond to the largest x_2, above 0.2, where one expects an EMC suppression – at least for quark PDF. For mid and slightly backward rapidities, one expects anti-shadowing, *i.e.* an excess of partons inducing an excess of Υ. Finally, the forward domain – where x_2 becomes small – should be subject to parton shadowing,

giving a reduction of the yield.

Our findings are as follows: in the most backward region, studied by PHENIX, the suppression of the Υ yield in the dAu data may be a first hint that the EMC suppression of the gluon distribution is stronger than the quark one. It is probably the very first observation of such an effect, whose quantitative understanding may in the future provide us with fundamental information on the internal dynamics of heavy nuclei.

Due to the large scale set in by the Υ mass, shadowing is found too feeble to reproduce data at $y > 0$. Moreover, the data at $y \simeq 0$ does not exhibit any excess which would pin down anti-shadowing. This motivated our study of the recently revived medium-induced fractional energy loss, this mechanism which would also explain the anomalous suppression of the forward J/ψ at E866 and NA3 in pA [4].

We have shown that –at variance with the J/ψ case [26]– gluon shadowing has, for any nPDF fits, a small effect at the x_2 and Q^2 of forward-Υ production at RHIC. An x_2 scaling of the nuclear effects is thus not expected. Provided that (fractional) energy loss is the dominant effect at work in the forward region, an x_1 scaling is expected, which exhibits an x_F scaling in the forward region where $x_1 \simeq x_F$, in analogy with [37, 10].

For bottomonia, whose survival probability to escape the Au nucleus should be large and whose shadowing suppression is found small, we argued that a new mechanism such as this fractional energy loss seems to be required. In the J/ψ case, it is rather allowed. The same mechanism may still apply for $y \simeq 0$ – still in the small angles domain at RHIC – and also elegantly explains the trend of the Υ STAR data. Such an effect provides an alternative explanation for the strong forward-J/ψ suppression in dAu as seen by PHENIX [36]. Our results are confirmed in [35]. Quantitatively, Υ data are better explained if the $b\bar{b}$ pair is produced at short distances in a colour-singlet state with a hard gluon as in [27], as opposed to a production in a colour-octet state. The picture is less clear for J/ψ.

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